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Corrosion-Fatigue Cracking in Al 7075 Alloys

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14. ABSTRACT

An investigation was carried out to characterize the effect of aging, environment (include [NaCl] concentration), and load ratio on fatigue crack growth kinetics of Al 7075 alloy. The materials investigated were peakaged Al 7075-T651 and overaged Al 7075-T7351. The results indicate: (1) the fatigue crack growth rates and fatigue crack growth threshold, ΔK_{th}, for Al 7075-T651 and Al 7075-T7351 are comparable at similar stress ratios in each of the three test environments (vacuum, ambient air, and 1% NaCl solution); (2) irrespective of Al 7075 aging conditions and stress ratios, the fatigue crack growth rates are lowest in vacuum, followed by those in ambient air, and are highest in 1% NaCl; (3) for both Al 7075-T651 and Al 7075-T7351, the fatigue crack growth rates initially increase rapidly when [NaCl] increases from 0.001 to 1% and then remain unchanged when [NaCl] further increases from 1 to 15%; and (4) for both Al 7075-T651 and Al 7075-T7351, the fatigue crack growth rates are higher at higher stress ratio in all three environments and the ΔK_{th} progressively decreases as the load ratio increases.

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Aluminum alloys

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Contents

Introduction 1

Experimental Procedure 1

Results and Discussion 2
  Effect of Aging 2
  Effect of Environment 2
  Effect of [NaCl] Concentration 3
  Effect of Load Ratio 3

Conclusions 5

References 6

Appendix A – Figures 7

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INTRODUCTION

7000-series aluminum alloys, such as Al 7075, are extensively used in aircraft and space structures because of their high specific strengths, low cost, easy fabrication, and well established manufacturing industries. The yield strength of peakaged Al 7075-T651 and overaged Al 7075-T7351 are, respectively, 500 and 430 MPa. These aluminum alloys are often exposed to the unique naval environments such as saltwater, salt fog, and near-coastal ocean spray.

The peakaged 7075-T651 is very susceptible to stress-corrosion cracking (SCC) in saltwater environment and has very low stress-corrosion cracking threshold stress intensity (K_{1SCC}) (references 1-2). The overaged Al7075-T7351, however, exhibits significantly better SCC resistance and is the preferred aluminum alloy for aircrafts built after 1980s. However, both peakaged Al 7075-T651 and overaged Al 7075-T7351 are susceptible to corrosion-fatigue crack growth under cyclic loading conditions. Previous studies (references 2-9) have shown that the moisture in the ambient air and saltwater can significantly increase the fatigue crack growth rates of aluminum alloys. In ambient air, the extent of increase in fatigue crack growth rates is affected by the water vapor partial pressure and cyclic frequency. In water and saltwater environment, on the other hand, aluminum alloys exhibited little or no effect of frequency. The enhancement of fatigue crack growth by water vapor and saltwater in the aluminum alloys was caused by the hydrogen embrittlement mechanism in which hydrogen was produced through surface reaction of water with freshly created fatigue surface (references 3, 8, and 10). However, many of the previous studies were focused on the effect of environment on the Stage 2 fatigue crack growth rates of aluminum alloys. The environmental effect on the near-threshold fatigue crack growth of aluminum alloys, particularly the fatigue crack growth threshold stress intensity, ΔK_{th}, below which the fatigue crack would not propagate, have not been systematically investigated.

A study was conducted to determine the effects of aging conditions (peakaged Al 7075-T651 and overaged Al 7075-T7351), environments (vacuum, ambient air, and saltwater with [NaCl] concentration varying from 0.001 to 15%), and load ratio ($R = 0.1$ to 0.85) on fatigue crack growth kinetics (Stages 1 and 2 and ΔK_{th}) of Al 7075 aluminum alloys. The results are compiled into this report.

EXPERIMENTAL PROCEDURE

Materials used in this study were (1) peakaged 63.5 mm-thick Al 7075-T651 plate and (2) overaged 63.5 mm-thick Al 7075-T7351 plate. The Al 7075 plates have nominal chemical composition of Zn: 5.6 %, Mg: 2.5 %, Cu: 1.6 %, Cr: 0.23 %, Fe: max 0.5 %, Si: 0.4 %, Ti: max 0.2 %, and Al: balance. The typical yield strengths for Al 7075-T651 and Al 7075-T7351 are, respectively, 503 and 435 MPa.

For fatigue crack growth studies, 12.7-mm-thick, 64.8-mm-wide wedge-opening-load (WOL) fracture mechanics specimens, with crack propagation direction perpendicular to the plate rolling direction (stort-transverse, ST), were used. The stress-intensity factor range

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(ΔK) for the WOL specimens was computed from the relationship (reference 11):

$$\Delta K = [\Delta P/(BW^{1/2})]\,[(2 + a/W)(0.8072 + 8.858\,(a/W) - 30.23\,(a/W)^2 + 41.088\,(a/W)^3 - 24.15\,(a/W)^4 + 4.951\,(a/W)^5]/(1 - a/W)^{3/2}, \quad (1)$$

where ΔP = applied load amplitude, B = specimen thickness, W = specimen width, and a = crack length. The fatigue test environments included vacuum (< 6×10^{-6} Pa background pressure), ambient air (20 °C and 42% relative humidity), and in saltwater solution with [NaCl] concentration varying from 0.001 to 15 wt%. For saltwater fatigue crack growth experiments, a corrosion inhibitor (0.02 M $Na_2Cr_2O_7$, 0.07 M $MaC_2H_3O_2$, and $HC_2H_3O_2$ to pH 4) is added to prevent the crack tip corrosion product forming and the associated corrosion product induced wedging phenomenon. The fatigue crack growth experiments were conducted in accord with ASTM E647 with a cyclic load frequency of 10 Hz, a sine waveform, and load ratios, R, ranging from 0.1 to 0.8. Fatigue crack length and fatigue crack growth rate were continuously monitored by a compliance technique. After fatigue tests, the fatigue-fractured surfaces were studied by scanning electron microscopy (SEM).

RESULTS AND DISCUSSION

EFFECT OF AGING

The effects of aging on Al 7075 are shown in Fig. A-1 by comparing the fatigue crack growth kinetic of peakaged Al 7075-T651 and overaged Al 7075-T7351 in vacuum (Fig. A-1a), ambient air (Fig. A-1b), and 1% NaCl solution (Fig. A-1c). Furthermore, the comparisons are made at a low load ratio of R = 0.1 and at high load ratio of R = 0.7 in vacuum and R = 0.85 in air and in 1% NaCl. For fatigue crack growth test at high stress ratio in vacuum, the transition from near-threshold Stage 1 crack growth to near-instability Stage 3 crack growth is very steep and the clip gauge-based compliance test method limits the high load ratio to R = 0.7.

As shown in Fig. A-1, the fatigue crack growth rates and fatigue crack growth threshold, ΔK_{th}, for peakaged Al 7075-T651 and overaged Al 7075-T7351 are comparable at similar stress ratios in each of the three test environments. For example, the ΔK_{th} obtained at R = 0.85 in 1% NaCl is about 1 MPa√m for both Al 7075-T651 and Al 7075-T7351 as shown in Fig. A-1c. This observation is interesting as the peakaged Al 7075-T651 is very susceptible to stress-corrosion cracking (SCC) with stress-corrosion cracking threshold stress intensity (K_{1SCC}) of 6 MPa√m, while the overaged Al 7075-T7351 is resistant to SCC with its K_{1SCC} about 20 MPa√m. However, under cyclic loading conditions, the peakaged Al 7075-T651 and overaged Al 7075-T7351 perform similarly, even in aggressive saltwater environments.

EFFECT OF ENVIRONMENT

The effects of environment on fatigue crack growth of peakaged Al 7075-T651 and overaged Al 7075-T7351 are shown, respectively, in Figs. A-2 and A-3. The test environments ranged from inert vacuum, ambient air, and 1% NaCl solution. As shown in

Figs. A-2 and A-3, irrespective of Al 7075 aging conditions and stress ratios, the fatigue crack growth rates are lowest in vacuum, followed by those in ambient air, and are highest in 1% NaCl. Depending on applied stress intensity, the fatigue crack growth rates in air are as much as two orders-of-magnitude higher than those in vacuum. The fatigue crack growth rates obtained in 1% NaCl are up to an order-of-magnitude higher than those in ambient air. Furthermore, the fatigue crack growth threshold stress intensity factor, ΔK_{th}, below which the crack will not grow, obtained in vacuum is significantly higher than those in ambient air and in 1% NaCl. It is interesting to note in Figs. A-2 and A-3, although fatigue crack growth rates in 1% NaCl are higher than those from ambient air, the ΔK_{th} obtained in ambient air and in 1% NaCl are comparable.

The observed environmental effects on fatigue crack growth of Al 7075-T651 and Al 7075-T7351 are consistent with previous investigations (references 3, 4, 5, and 7). The water vapor in ambient air is known to react with freshly created aluminum fatigue fracture surfaces. The hydrogen thus generated from water vapor/aluminum reaction enters into fatigue crack tip region and accelerates fatigue crack growth and lowers ΔK_{th} via a hydrogen embrittlement mechanism (references 3, 5, and 8). In saltwater environment, the same water/aluminum surface reaction produces hydrogen and enhance fatigue crack growth. It is speculated that, in the Stage 2 fatigue crack growth region, the complex electrochemical reactions occurred at the crack tip may enhance hydrogen entry and cause additional embrittlement and higher fatigue crack growth rates than those obtained in ambient air. In the near-threshold Stage 1 region, where fatigue crack growth rates are slowest and the time for water/aluminum surface reactions are longest, it is speculated that the surface reactions in ambient air and in saltwater are saturated and a comparable amount of hydrogen enters the crack tip region and, hence, the similar ΔK_{th} in ambient and in 1% NaCl.

EFFECT OF [NaCl] CONCENTRATION

The effects of [NaCl] concentration on fatigue crack growth of Al 7075-T651 and Al 7075-T7351 are shown, respectively in Figs. A-4 and A-5. Both peakaged Al 7075-T651 and overaged Al 7075-T7351 exhibit similar [NaCl] dependencies at $R = 0.1$ and at $R = 0.85$. The fatigue crack growth rates in diluted saltwater (0.001 wt% NaCl) are the slowest in both Al 7075-T651 and Al 7075-T7351. The fatigue crack growth rates increase rapidly when [NaCl] increases from 0.001 to 1%. Above 1% [NaCl], the fatigue crack growth rates stop increasing as the crack growth rates are essentially the same in 1% and in 15% [NaCl]. The ΔK_{th} does not change as [NaCl] ranges from 0.001 to 15%, as shown in Fig. 6. The ΔK_{th} at a high load ratio of $R = 0.85$ is 1 $MPa\sqrt{m}$ for both Al 7075-T651 and Al 7075-T7351 in solutions with [NaCl] from 0.001 to 15%. At lower load ratio of $R = 0.1$, ΔK_{th} is in the narrow range between 2 and 2.5 $MPa\sqrt{m}$ for both Al 7075 alloys.

EFFECT OF LOAD RATIO

The effects of load ratio on fatigue crack growth of Al 7075-T651 and Al 7075-T7351 in vacuum, ambient air, and 1% NaCl solution are shown, respectively, in Figs. A-7 and A-

8. The load ratios selected are R = 0.1 and R = 0.85 for tests in vacuum and ambient environments, while an additional load ratio of R = 0.5 was added for tests 1% NaCl solution. As shown in Figs. 7 and 8, the fatigue crack growth rates are higher at higher stress ratio in all three environments. For both Al 7075-T651 and Al 7075-T7351, the ΔK_{th} obtained in vacuum at R = 0.1 and R = 0.85 are comparable as shown in Figs. A-7a and A-8a. However, in more aggressive environments, such as ambient air and 1% NaCl solution, the fatigue crack growth curve shifts to the left and ΔK_{th} is lower when load ratio increases, as shown in Figs. A-7b and A-7c and Figs. A-8b and A-8c.

The effects of load ratio on ΔK_{th} are shown in Fig. A-9 for Al 7075-T651 and Al 7075-T7351 in vacuum, ambient air, and 1% NaCl solution. As shown in Fig. A-9, ΔK_{th} decreases with increasing load ratio. The decrease in ΔK_{th} is somewhat less in vacuum environment.

CONCLUSIONS

The fatigue crack growth rates and fatigue crack growth threshold, ΔK_{th}, for peakaged Al 7075-T651 and overaged Al 7075-T7351 are comparable at similar stress ratios in each of the three test environments (vacuum, ambient air, and 1% NaCl solution).

Irrespective of Al 7075 aging conditions and stress ratios, the fatigue crack growth rates are lowest in vacuum, followed by those in ambient air, and are highest in 1% NaCl. The observed environmental effect in Al 7075 alloys is consistent with a hydrogen-enhanced cracking mechanism.

For both peakaged Al 7075-T651 and overaged Al 7075-T7351, the fatigue crack growth rates increase rapidly when [NaCl] increases from 0.001 to 1%. Above 1% [NaCl], the fatigue crack growth rates stop increasing. The ΔK_{th}, however, remains constant and does not change as [NaCl] ranges from 0.001 to 15%.

For Al 7075-T651 and Al 7075-T7351, the fatigue crack growth rates are higher at higher stress ratio in all three environments. The ΔK_{th} progressively decreases as the load ratio increases.

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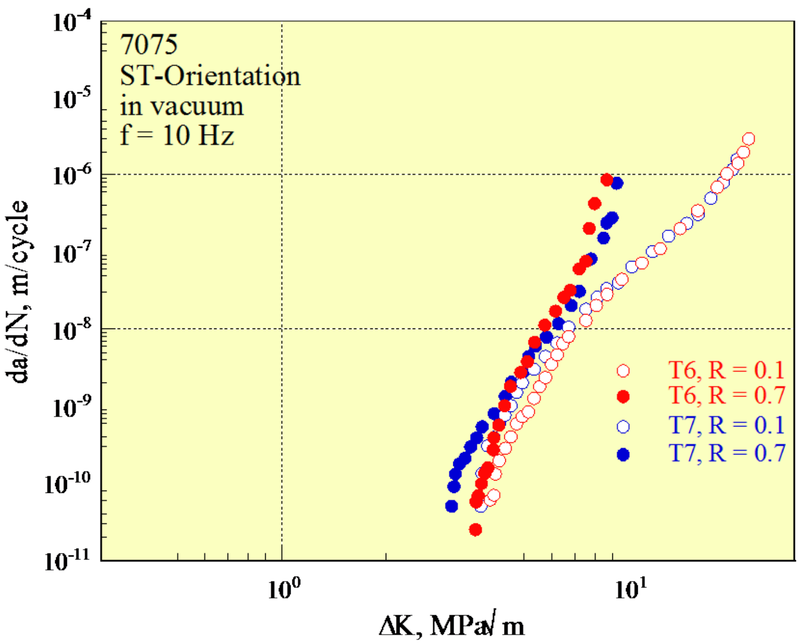
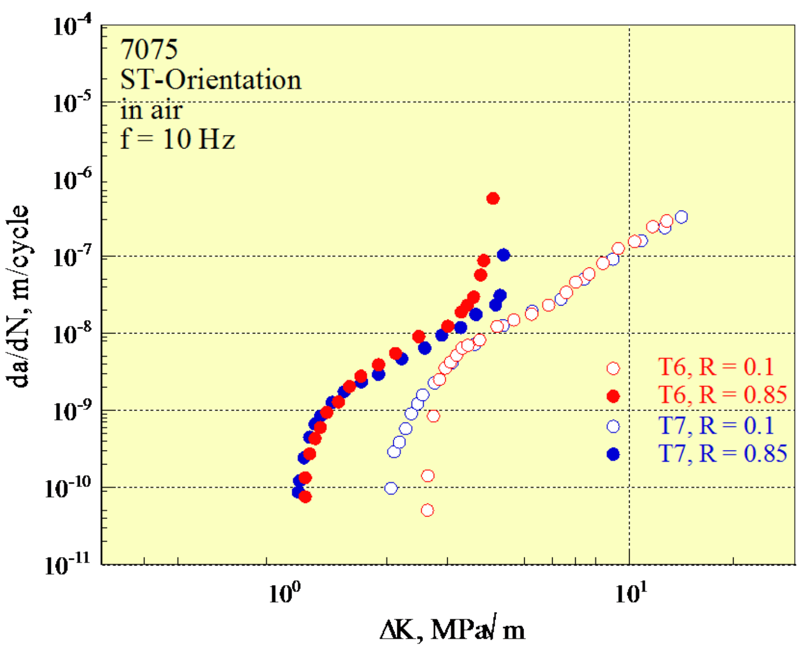
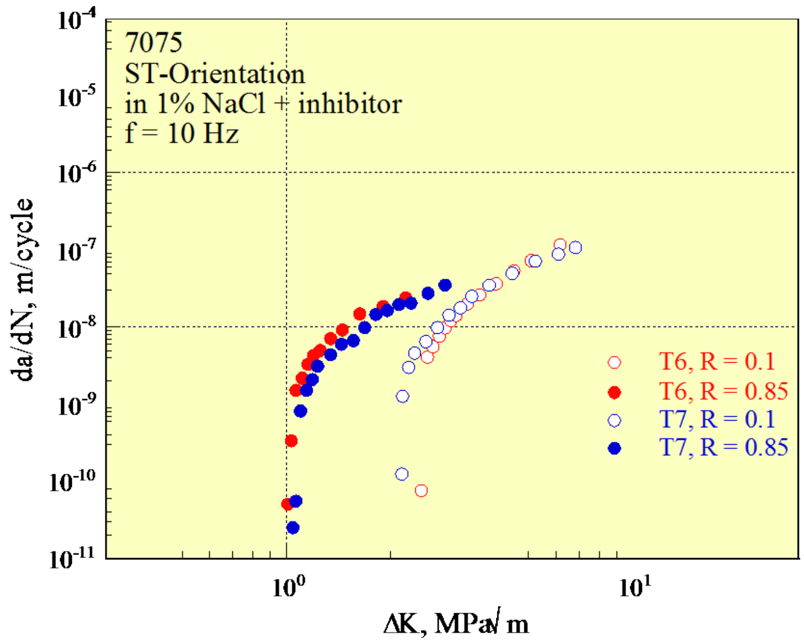
APPENDIX A
FIGURES


7075
ST-Orientation
in vacuum
f = 10 Hz
T6, R = 0.1
T6, R = 0.7
T7, R = 0.1
T7, R = 0.7
da/dN, m/cycle
ΔK, MPa√m

(a)

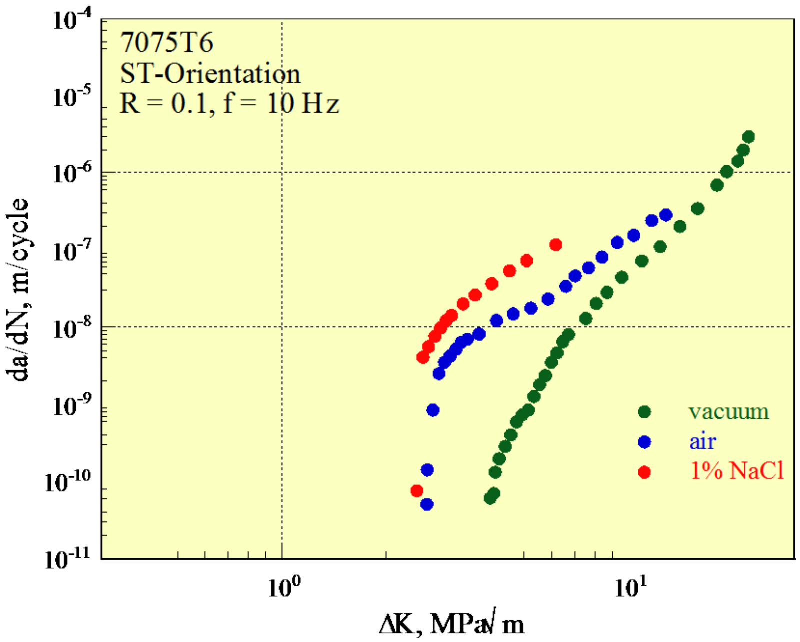

7075
ST-Orientation
in air
f = 10 Hz
T6, R = 0.1
T6, R = 0.85
T7, R = 0.1
T7, R = 0.85
da/dN, m/cycle
ΔK, MPa√m

(b)

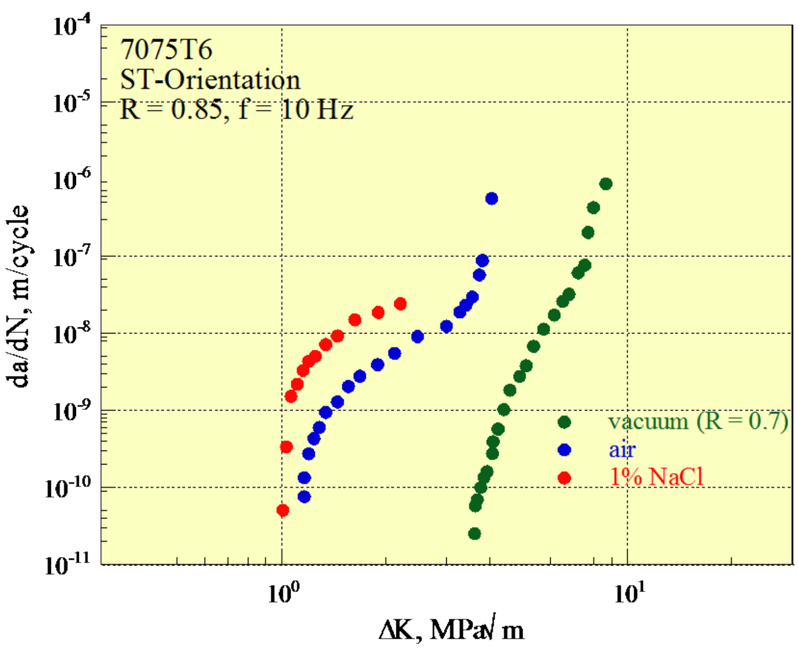


(c)

Figure A-1: Comparison of fatigue crack growth of peakaged Al 7075-T651 and overaged Al 7075-T7351 in (1) vacuum, (b) ambient air, and (c) 1% NaCl.

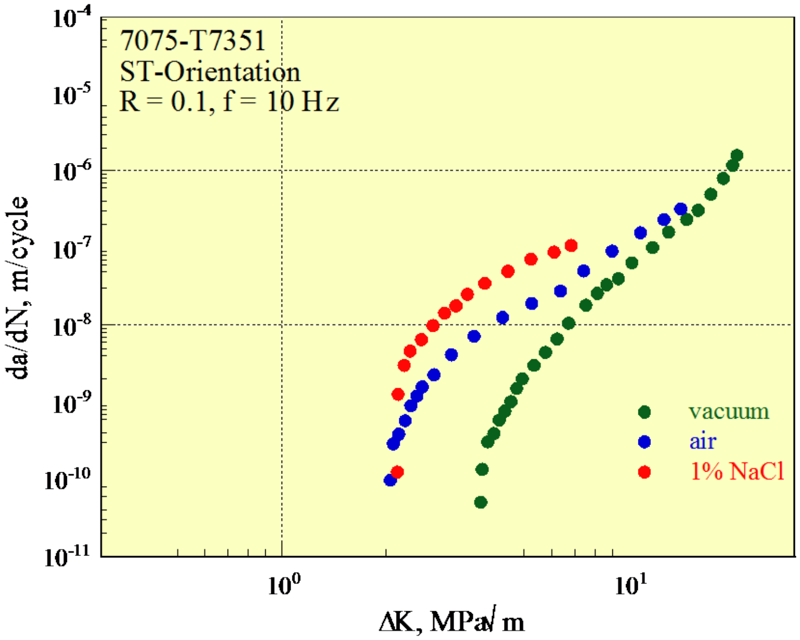


(a)



(b)

Figure A-2: Comparison of fatigue crack growth kinetic of Al 7075-T651 in vacuum, ambient air, and 1% NaCl at (a) R = 0.1 and (b) R = 0.85.



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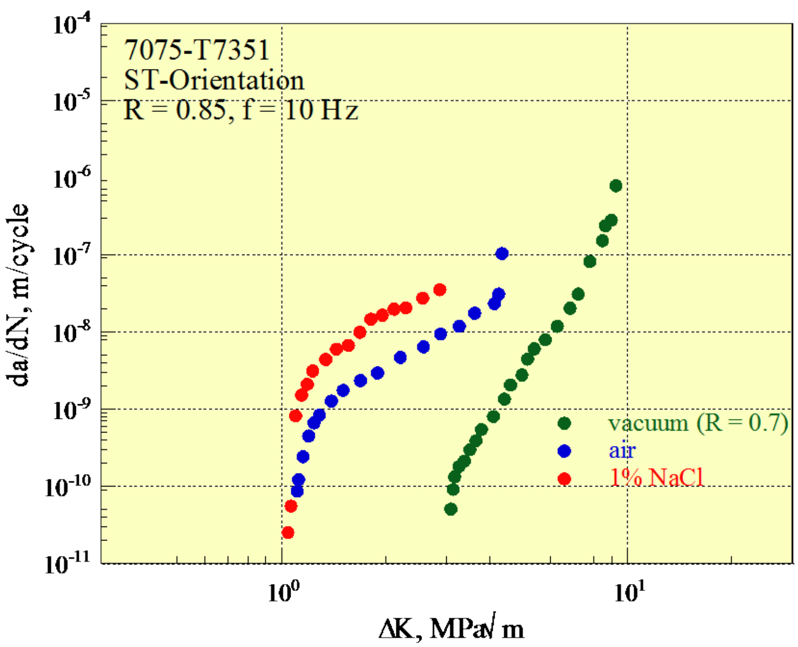


(b)

Figure A-3: Comparison of fatigue crack growth kinetic of Al 7075-T7351 in vacuum, ambient air, and 1% NaCl at (a) R = 0.1 and (b) R = 0.85.

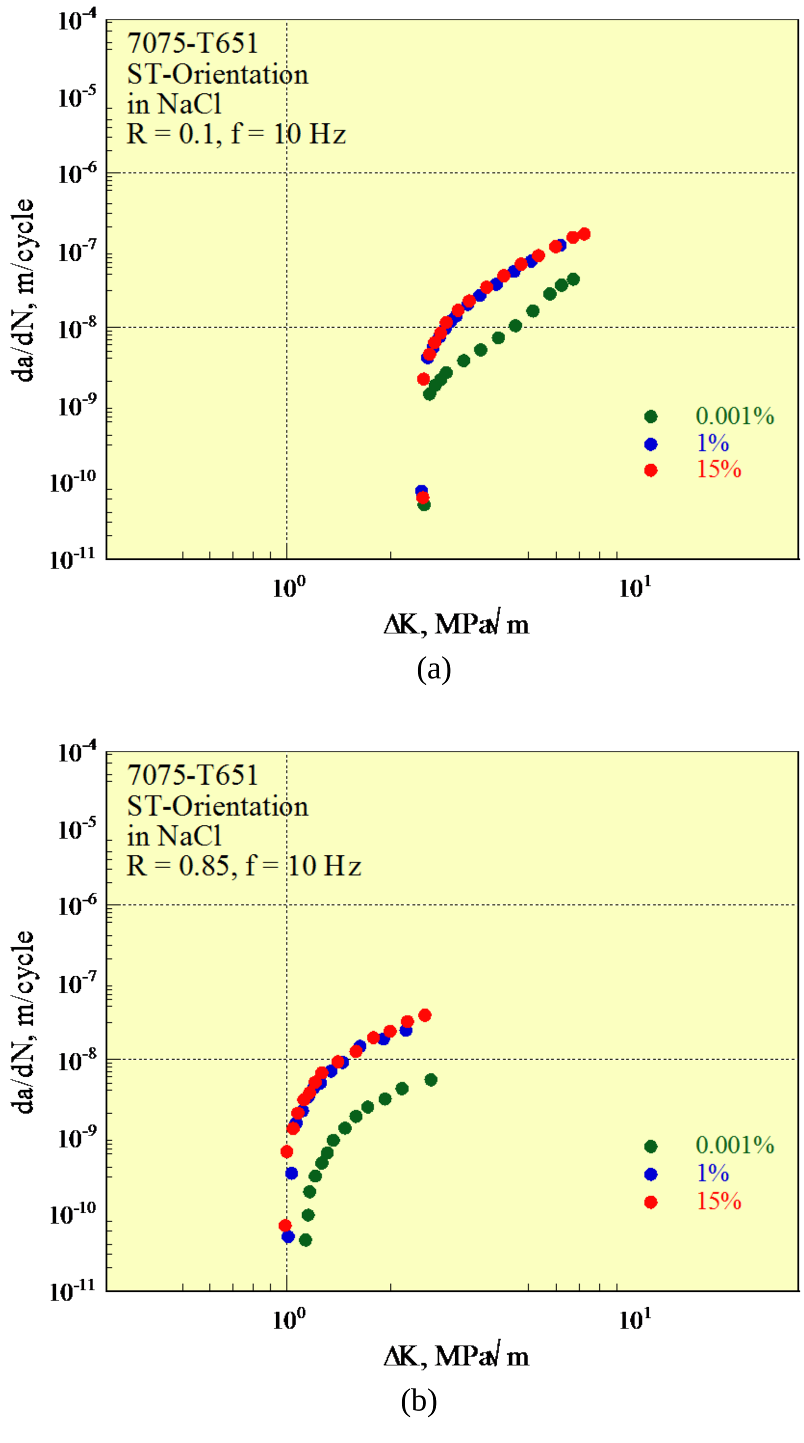
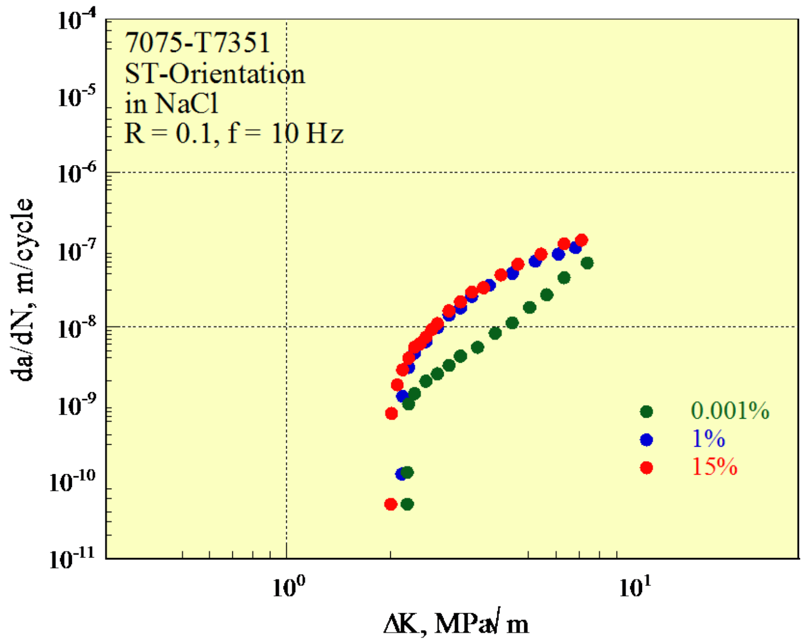


Figure A-4: Effect of [NaCl] concentration on fatigue crack growth in Al 7075-T651 at (a) R = 0.1 and (2) R = 0.85.



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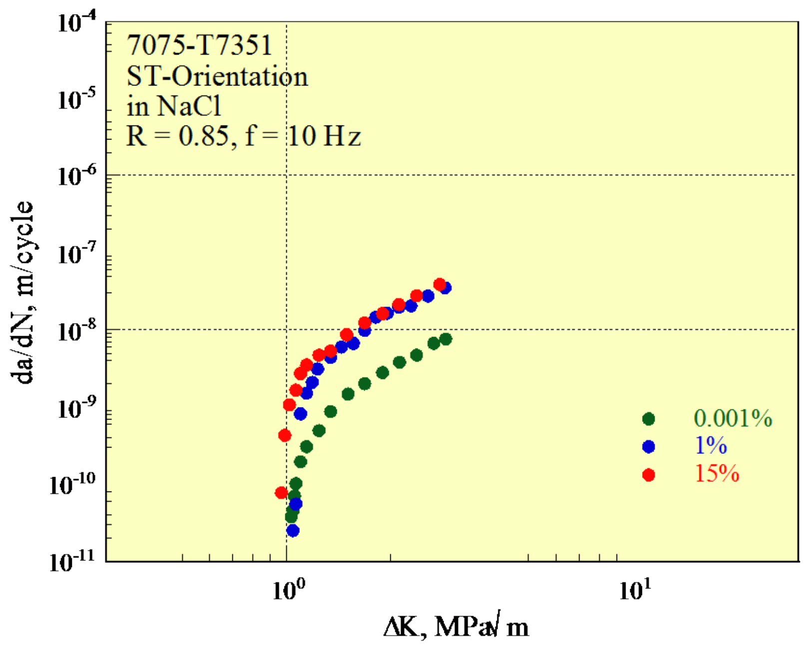
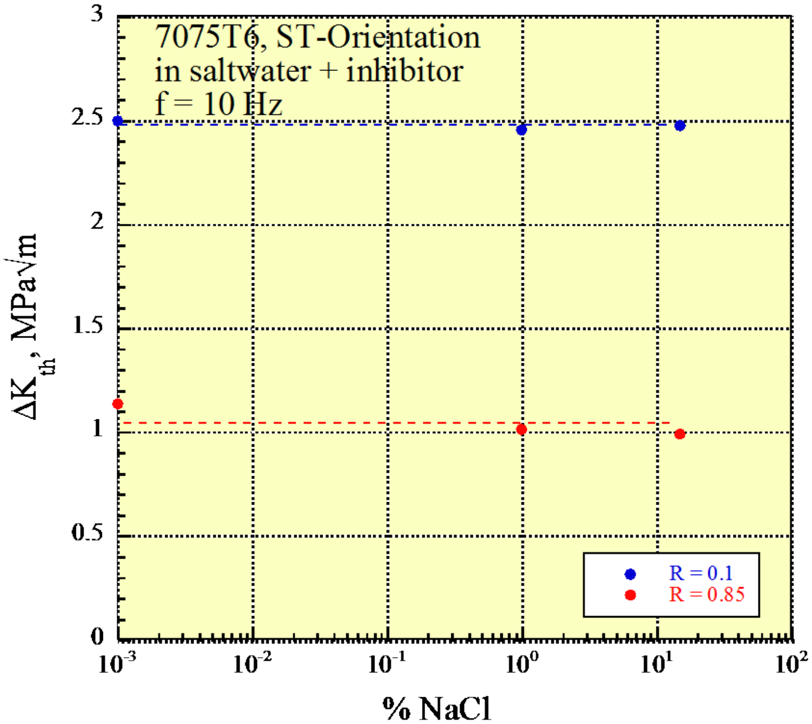


(b)

Figure A-5: Effect of [NaCl] concentration on fatigue crack growth in Al 7075-T7351 at (a) R = 0.1 and (2) R = 0.85.



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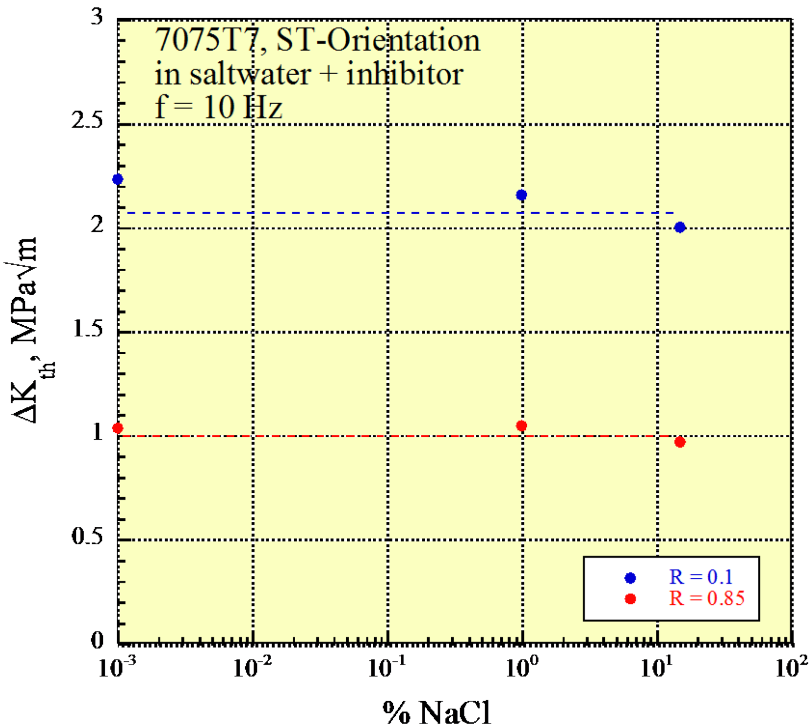
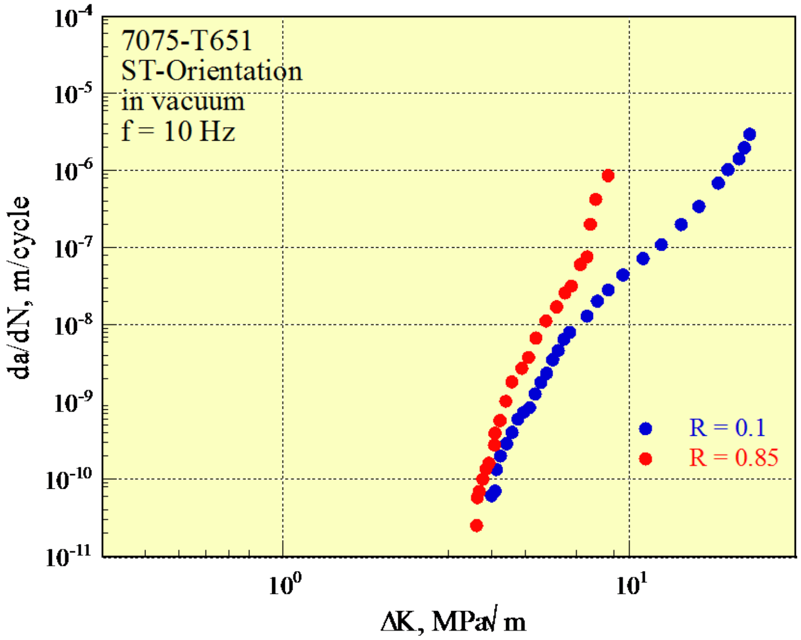
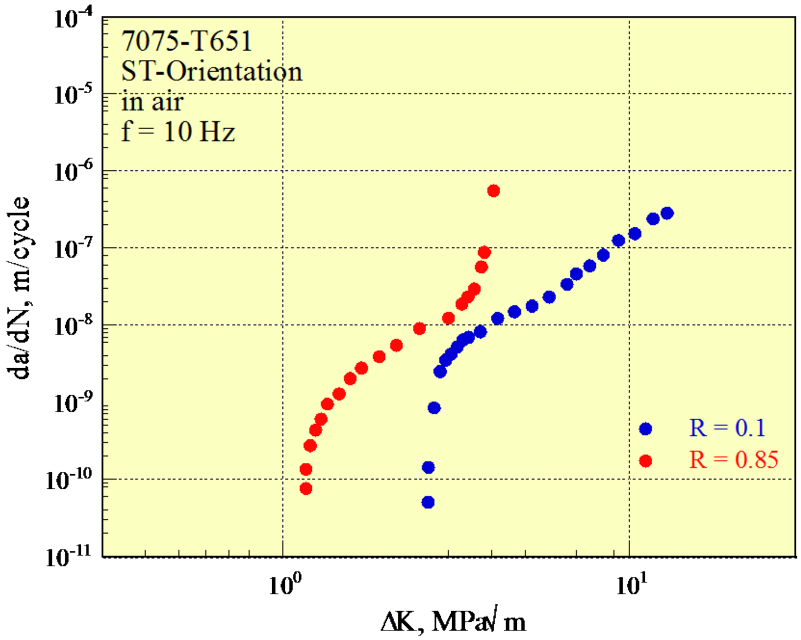


(b)

Figure A-6: Effect of [NaCl] concentration on fatigue crack growth threshold, ΔK_{th}, in (a) Al 7075-T651 and (b) Al 7075-T7351.


7075-T651
ST-Orientation
in vacuum
f = 10 Hz
R = 0.1
R = 0.85
da/dN, m/cycle
ΔK, MPa√m

(a)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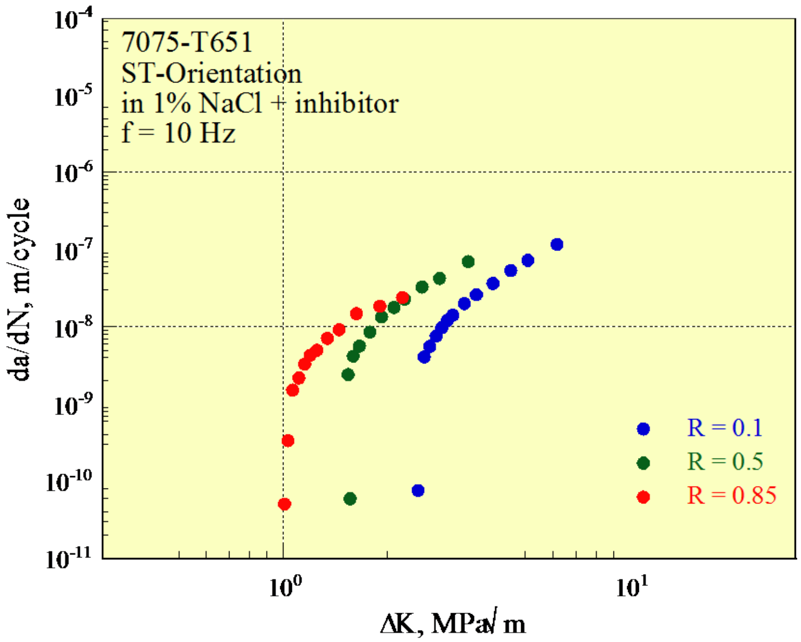
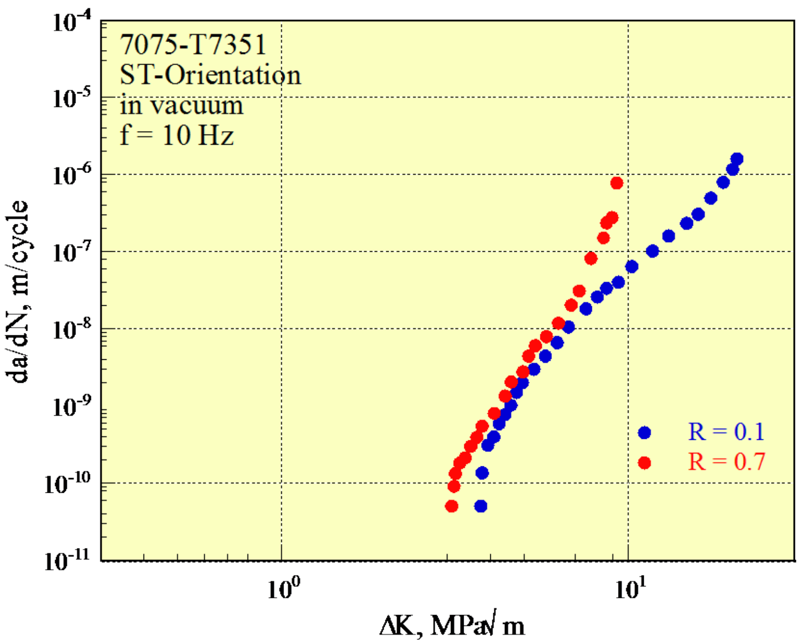
R = 0.1
R = 0.85
da/dN, m/cycle
ΔK, MPa√m

(b)

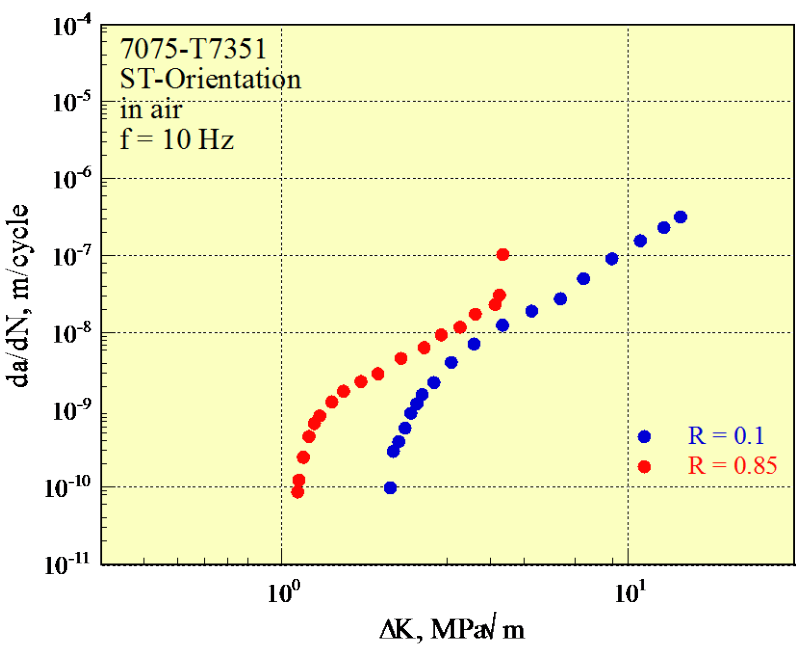


(c)

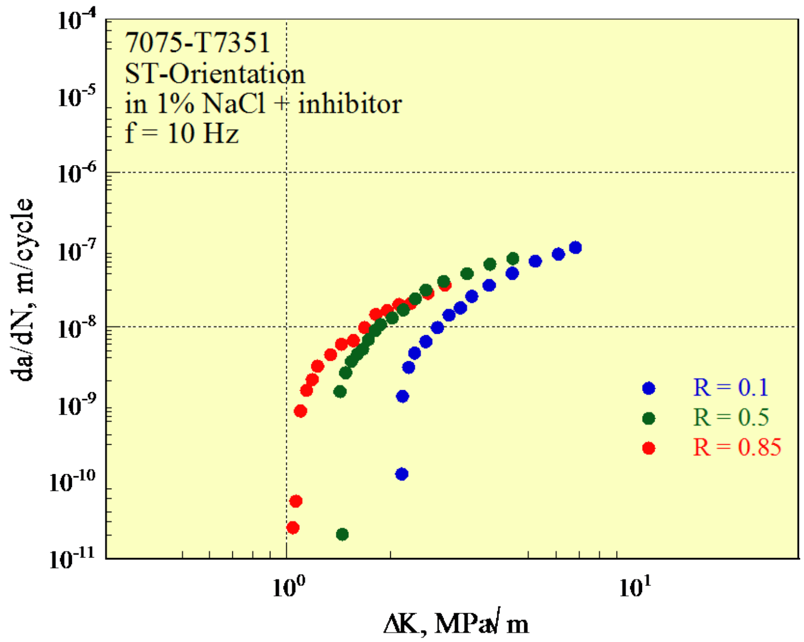
Figure A-7: Effect of load ratio on fatigue crack growth of Al 7075-T651 in (a) vacuum, (b) ambient air, and (c) 1% NaCl.


7075-T7351
ST-Orientation
in vacuum
f = 10 Hz
R = 0.1
R = 0.7
da/dN, m/cycle
ΔK, MPa√m
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{0}
10^{1}

(a)

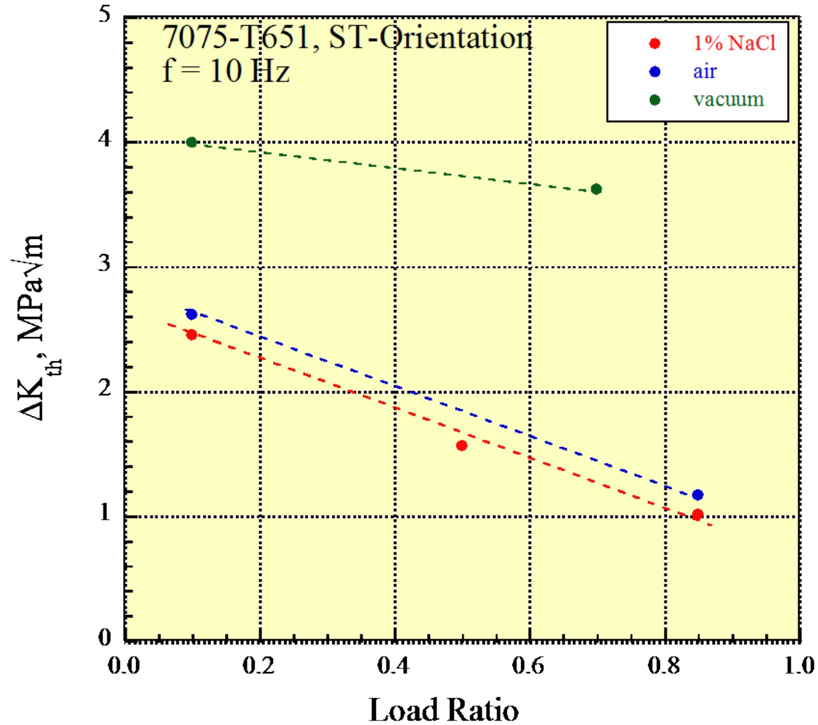

7075-T7351
ST-Orientation
in air
f = 10 Hz
R = 0.1
R = 0.85
da/dN, m/cycle
ΔK, MPa√m
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{0}
10^{1}

(b)

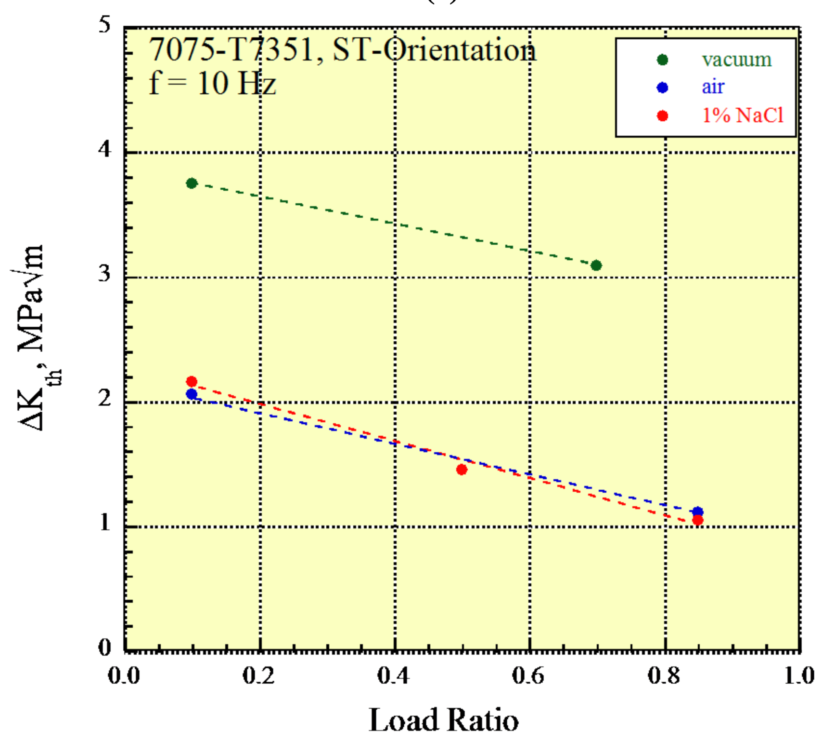


(c)

Figure A-8: Effect of load ratio on fatigue crack growth of Al 7075-T7351 in (a) vacuum, (b) ambient air, and (c) 1% NaCl.



(a)



(b)

Figure A-9: Effect of load ratio on ΔK_{th} in vacuum, ambient air, and 1% NaCl for (a) Al 7075-T651 and (b) Al 7075-T7351.